APPLICATION OF QUANTUM 1/F NOISE THEORY TO $Hg_{1-x}Cd_xTe$ INFRARED DETECTORS

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Both $Hg_{1-x}Cd_xTe$ n P junctions and MIS structures have been studied as infrared detectors, using the Quantum 1/f Noise approach. The quantum 1/f theory predicts a proportionality of 1/f noise to the reciprocal lifetime of the carriers, and a peculiar analytical dependence on the bias voltage. Both relations have received excellent experimental verification with the help of A. van der Ziel of the University of Minnesota and his group, and with the help of my assistant Q. Peng. A high frequency impedance measurement method was developed for measur-

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) ing the lifetime of the carriers accurately. A numerical code was developed for the calculation of noise, including quantum 1/f noise, in infrared detector junctions. The quantum 1/f theory predicts higher 1/f noise in the surface recombination current than in the bulk recombination current, due to both the surface potential jump and current concentration. Previous studies by Kleinpenning had included only an empirical mobility fluctuation effect, ignoring the recombination speed fluctuations which arise on equal footing in the quantum 1/f theory. Also the Green function for the diffusion equation was not included in the earlier Kleinpenning model. Our first principle quantum 1/f calculation led to suggestions for noise reductions. First a seminar was held at NVEOL in six consecutive sessions in January 1986. Then several advisory consultations were performed for the benefit of the DOD contractors producing the detectors (Rockwell, SBRC, TI), and the detector performance was subsequently improved by two orders of magnitude along the lines suggested. However, we do not claim that the improvements were caused by our contributions, although we may have been of help in clarifying the physics of quantum 1/f noise.

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Summary

The objective of this program was the application of quantum 1/f theory to infrared detectors and suggestion of possible improvements.

Both $Hg_{1-x}Cd_xTe$ n^+p junnctions and MIS structures have been studied as innfrared detectors on the basis of the Quantum 1/f Noise appoach. The quantum 1/f theory predicts both a proportionality of 1/f noise to the reciprocal lifetime of the carriers, and a peculiar analytical dependence on the bias voltage. Both relations have received excellent experimental verification with the help of A. van der Ziel of the University of Minnesota and his group, and with the help of my assistant Q. Peng. A high frequency impedance measurement method was developed for measuring the lifetime of the carriers accurately. A numerical code was developed for the calculation of noise, including quantum 1/f noise, in infrared detector junctions. The quantum 1/f theory predicts higher 1/f noise in the surface recombination current than in the bulk recombination current, due to both the surface potential jump and the current concentration effect. Previous studies by Kleinpenning had included only an empirical mobility fluctuation effect (Hooge formula), ignoring the recombination speed fluctuations which arise on equal footing with mobility fluctuations in the quantum 1/f theory. Also the Green function of the diffusion equation was not included in the earlier Kleinpenning model. Our first principle quantum 1/f calculation led to suggestions for noise reductions. First a seminar was held at NVEOL in six consecutive sessions in January 1986. Then several advisory consultations were performed for the benefit of the DOD contractors who fabricate the detectors (Rockwell, SBRC, TI), and the detector performance was subsequently inproved by two orders of magnitude along the lines suggested. However, we do not claim

that the inprovements were caused by our contributions, although we may have been of help in clarifying the physics of quantum 1/f noise.

During the period of this project I have first developed a second -quantized derivation of quantum 1/f noise limiting myself to two particles in the final state, and then I extended this derivation to the general case of N particles present in the final state. I also have derived the quantum 1/f cross correlations and the corresponding cross -correlation spectra, which are important for the calculation of quantum 1/f noise in kinetic coefficients such as the mobility and the diffusion coefficient of the current carriers in solids. In order to better explain the foundations of quantum 1/f theory, I have given a derivation of the quantum 1/f Schroedinger fields from quantum electrodynamics with the use of coherent states. Finally, I have given a direct derivation of the quantum 1/f effect in time and space. In terms of applications, a quantum 1/f noise study of MIS detectors was performed. Experimentally, with the collaboration of the group of Prof. A. van der Ziel, an excellent experimental verification of quantum 1/f theory was performed on semiconductor diodes, transistors and vacuum tubes, and a review article on the results of the experimental aplication and verification of my theory was published by A. van der Ziel in the Proceedings of IEEE in March 1988.

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I. INTRODUCTION

I.1 OVERVIEW

The present report will give a general description of the extensive work performed on $Hg_{1-x}Cd_xTe$ infrared detectors in the Scientific Service Program. This work was done along two major directions:

1. Application of the quantum 1/f theory to n^+p diode infrared detectors produced by epitaxial growth or by ion implantation, presented in Sec. II. This work was performed in cooperation with Prof. A. van der Ziel and his group.

2. Application to metal-insulator-semiconductor (MIS) infrared detector structures, presented in Sec. III. This section is dedicated to a detailed quantum 1/f noise study of an important type of infrared detector, the metal - insulator - semiconductor structure.

Sec. IV. lists the publications corresponding to this grant period.

At the III Conference on Quantum 1/f Noise and 1/f Noise in Minneapolis, April 28-29, 1988, Prof. C.M. Van Vliet also presented a quantum 1/f noise derivation in the Van Hove limit. At present our attention is focussed on applications of the newly calculated cross - spectra of quantum 1/f noise to $Hg_{1-x}Cd_xTe$ in order to further improve the accuracy of our quantum 1/f noise calculations in infrared detectors, and to find ways in which the noise can be further reduced.

I.2 SIMPLE DERIVATION OF CONVENTIONAL QUANTUM 1/f NOISE

The utilisation of infrared detectors at larger wavelengths and in the staring mode has made the limitations imposed by 1/f noise on the performance of n^+p diodes and MIS structures more stringent and conspicuous. On the other hand, the development of the quantum 1/f theory has provided us for the first time with a possibility to predict, model and calculate from first principles the various 1/f noise contributions affecting the many currents and processes which are of importance in the operation of infrared detectors.

The main purpose of our Scientific Service Program and of the present report is to apply this new knowledge of 1/f noise to n^+p diodes and MIS structures working as infrared detectors. We start here with a brief general description of quantum 1/f noise and continue in Sec. II with the inventory of various 1/f noise components present in the current of n^+p infrared detectors. In Sec. III.3 we analyze the quantum 1/f noise associated with the currents and processes of MIS structures discussed in Sec. III.2. In Sec. III.4 we compare the 1/f noise components in magnitude and determine their impact on the performance of MIS detectors. Finally, in Sec. III.5 we discuss the resulting 1/f noise limitations, and point out some possibilities of reducing the quantum 1/f noise in MIS devices. A similar discussion for n^+p diodes is given in Sec. II.2.

Quantum 1/f noise[1-5] is a fundamental fluctuation of physical cross sections and process rates, caused by the infrared - divergent coupling of current carriers to low frequency photons and other infraquanta. The physical origin of quantum 1/f noise is easy to understand. Consider for example Coulomb scattering of electrons on a center of force. The scattered electrons reaching a detector at a given angle away from the direction of the incident beam are described by DeBroglie waves of a frequency corresponding to their energy. However, some of the elecrons have lost energy in the scattering process, due to the emission of Bremsstrahlung. Therefore, part of the outgoing DeBroglie waves is shifted to slightly lower frequencies and interferes with the main, non-Bremsstrahlung, component, yielding beats. These beats present in the probability density along the direction of the scattered beam will be noticed in the detector as low frequency current fluctuations, and will be interpreted as fundamental cross section fluctuations. Although the wave function of each carrier is split into a Bremsstrahlung part and a non-Bremsstrahlung part, no quantum 1/f noise can be observed from a single carrier. A single carrier will only provide a pulse in the detector. Many carriers are needed to produce the 1/f noise effect, just as in the case of electron diffraction patterns. While incoming carriers may have been Poisson distributed, the scattered beam will exhibit super - Poissonian statistics or bunching due to quantum 1/f noise. The quantum 1/f effect is thus a two - particle effect, best described through the two - particle wave function and two - particle correlation function.

Let us estimate the magnitude of the quantum 1/f effect by starting with the classical (Larmor) formula $q\dot{\vec{v}}^2/3c^3$ for the power radiated by a particle of charge q and acceleration $\dot{\vec{v}}$. The acceleration can be approximated by a delta function $\dot{\vec{v}}(t) = \Delta\vec{v}\,\delta(t)$ whose Fourier transform $\Delta\vec{v}$ is constant. The one - sided spectral density of the emitted Bremsstrahlung power $2q(\Delta\vec{v})^2/3c^3$ is therefore also constant. The number $2q(\Delta\vec{v})^2/3hfc^3$ of emitted photons per unit frequency interval is obtained by dividing with the energy hf of one photon. The probability amplitude of photon emission $[2q(\Delta\vec{v})^2/3hfc^3]^{1/2}$ is given by the square root of this photon number spectrum, including also a phase factor. The beat term in the probability density $|\psi|^2$ is linear both in this Bremsstrahlung amplitude and in the non - Bremsstrahlung amplitude. Its spectral density will therefore be given by the product of the squared probability amplitude of photon emission with the squared non - Bremsstrahlung amplitude which is independent of f. The resulting spectral density of fractional probability density fluctuations is obtained by dividing with $|\psi|^4$ and is therefore

$$|\psi|^{-4} S_{|\psi|^2}(f) = 8q^2(\Delta\vec{v})^2/3hfNc^3 = 2\alpha A/fN = j^{-2}S_j(f), \tag{1.1}$$

where $\alpha = 2e^2/hc = 1/137$ is the fine structure constant and $\alpha A = 4q^2(\Delta\vec{v})^2/3hc^3$ is known as the infrared exponent in quantum field theory, and is known as the quantum 1/f noise coefficient, or Hooge constant, in electrophysics.

The spectral density of current density fluctuations is obtained by multiplying the probability density fluctuation spectrum with the squared velocity of the outgoing particles. When we calculate the spectral density of fractional fluctuations, the velocity simplifies and therefore Eq. (1.1) also gives the fractional spectrum of current fluctuations $S_j(f)$, as indicated above. The quantum 1/f noise contribution of each carrier is independent, and therefore the quantum 1/f noise from N carriers is N times larger; however, the current j will also be N times larger, and therefore in Eq. (1.1) a factor N was included in the denominator for the case in which the cross section fluctuation is observed on N carriers simultaneously.

The fundamental fluctuations of cross sections and process rates are reflected in various kinetic coefficients, such as the mobility μ and the diffusion constant D, the surface and bulk recombination speeds s and recombination times τ, the rate of tunneling j_t and the thermal diffusivity. Therefore, the spectral density of fractional fluctuations in all these coefficients is given also by Eq. (1). This is true in spite of the fact that each carrier will undergo many consecutive scattering processes in the diffusion process. The quantum 1/f noise in the mobility and in the diffusion coefficient is practically the same as the quantum 1/f noise in a single representative scattering event which limits the mobility or the diffusion coefficient.

Due to the rapid relaxation of concentration fluctuations, the quantum 1/f fluctuations of scattering cross sections will only be reflected by the fluctuations of the mobility and the diffusion constant of the carriers, and not by fluctuations in the concentration of carriers.

For large devices the concept of coherent state quantum 1/f noise was introduced[11, 12]. In this case the Hooge parameter α_H may be written

$$\alpha_H = (\alpha_H)_{coh} = 2\alpha/\pi = 4.6\ 10^{-3} \qquad (1.2)$$

where $\alpha = 1/(137)$ is the fine structure constant. This is of the same order of magnitude as the empirical value $\alpha_H = 2\ 10^{-3}$ that Hooge found for long devices. It is therefore proposed that Hooge's emprical value for α_H is due to coherent state quantum 1/f noise, so that it has a very fundamental origin.

For small devices (e.g., of size $L < 10\ \mu m$) we apply conventional, or incoherent[2-8], quantum 1/f noise which is just the cross section fluctuation introduced above in Eq. (1.1). In that case α_H may be written

$$\alpha_H = (\alpha_H)_{incoh} = (4\alpha/3\pi)\ (\Delta\vec{v})^2/(c^2) \qquad (1.3)$$

where $\Delta\vec{v}$ is the change in the velocity of the carriers in the interaction process considered. This expression holds for any 1/f noise source describable by fluctuating cross sections. Since usually $(\Delta v^2/c^2) << 1$, except for carriers with a very small effective mass, we now have $\alpha_H < 3.1\ 10^{-3}$. This may explain the low values of α_H (in the range of $\alpha_H = 10^{-5} - 10^{-9}$) for very small devices. In between one can introduce a parameter $s = f(L/L_0)$ where L_0 is a characteristic size and write[12].

$$\alpha_H = (\alpha_H)_{incoh} /(1 + s) + (\alpha_H)_{coh} \cdot s/(1 + s), \qquad (1.4)$$

with $s \ll 1$ for $L/L_0 \ll 1$ and $s \gg 1$ for $L/L_0 \gg 1$. According to this rough approximation[12], $L_0 = 100\mu m$ for samples with a concentration c of carriers of $10^{15} cm^{-3}$ and varies proportional to $c^{-1/2}$. This describes the transition from Eq. (1.2) to Eq. (1.3) when one goes to devices with smaller and smaller sizes, as we shall see below in Eq. (3.21). A suggestion for the calculation of s was presented by the author at the Rome 1985 Conf. on Noise in Physical Systems and 1/f Noise*: $s = 2e^2N'/m^*c^2 = N'/2\ 10^{12}$, where N' is the number of carriers per unit length of the sample or device in the direction of current flow.

When we apply Eq. (1.1) to a certain device we first need to find out which are the cross sections which limit the current, and then we have to determine both the velocity change $(\Delta \vec{v})$ of the scattered carriers and the number N of carriers simultaneously used to test each of these cross sections.

II. n+ p DIODE INFRARED DETECTORS

II.1. QUANTUM 1/f NOISE SOURCES APPLICABLE TO n+ p DIODES

The various quantum 1/f noise sources present in n^+p diodes which we will consider here, have in common that they can be described by Eq. (1.3) with a $\Delta\vec{v}^2$ value described by an effective energy $E = qV_o$, where V_o is an effective potential which accelerates the carriers

$$(\Delta\vec{v}^2)/c^2 = 2E/m^*c^2 = 2qV_o/m^*c^2. \qquad (2.1)$$

In various quantum 1/f noise sources the applicable velocity change $\Delta\vec{v}$ determines the Hooge constant:

(a) Recombination quantum 1/f noise in the bulk space charge region[6]:

$$S_{I(f)} = \alpha_H q |I_{gr}| \left[\tanh(qV/2KT)\right] / f(\tau_{no} + \tau_{po}); \qquad (2.2)$$

$$H = (4\alpha/3\pi)\left[2q(V_{dif}-V) + 3KT\right]\left\{(m_h^*)^{1/2} + (m_p^*)^{1/2}\right\}^{-2} c^{-2},$$

where $I_{gr} = qAWn_i(e^{qV/2KT} - 1)/(\tau_{no} + \tau_{po})$ is the recombination current, τ_{no} and τ_{po} the Shockley-Hall-Read lifetimes, V the applied voltage and V_{dif} the diffusion potential of the junction. Introducing an "effective carrier number" $N_{eff} = |I_{gr}|(\tau_{no}+\tau_{po})/q\left[\tanh(qV/2KT)\right]$, Eq. (2.2) may be written in the form

$$S_I(f) = \alpha_H I_{gr}^2 / fN_{eff}. \qquad (2.2a)$$

(b) Quantum 1/f noise in the surface recombination current of n^+-p diodes. This effect is caused by quantum 1/f fluctuations of the surface recombination cross sections. The calculation is similar to the previous (bulk) case, but the GR process is localized at the surface, and the additional electric field arising from the potential jump 2U at the interface between the bulk and the oxide and passivation layers will lead to increased velocity changes of the carriers in the recombination process and to larger α_H values. Including also the quantum 1/f mobility fluctuation noise of the spreading resistance caused by the concentration of generation and recombination currents at the intersection of the depletion region with the surface of the diode, we obtain a current noise contribution

$$S_I(f) = \alpha'_H q |I'_{gr}| \left[\tanh(qV/2kT)\right] / f(\tau'_{no} + \tau'_{po})$$

$$+ \alpha_\mu (I'_{gr})^2 / \pi n f P \left[\ln(A/W^2)\right]^2, \qquad (2.3)$$

$$\alpha'_H = (4\alpha/3\pi)\left[2q(V_{dif}+U-V)+3kT\right]\left\{(m_n^*)^{1/2} + (m_p^*)^{1/2}\right\}^{-2} c^{-2} \qquad (2.3a)$$

Here the primed quantities refer to the surface, i.e. we have introduced the surface GR current I'_{gr}, the lifetimes in the vicinity of the surface and the α'_H parameter for surface recombination. P is the perimeter, A the area and W the width of the junction. The quantum 1/f mobility fluctuation part is expressed in terms of the global α_μ parameter which includes all types of scattering weighed with the appropriate mobility ratio factors. Introducing again an "effective carrier number" $N'_{eff} = |I'_{gr}| (\tau'_{no}+\tau'_{po})/q\left[\tanh(qV/2kT)\right]$, the first term of Eq. (2.3) may also be written in the form:

$$S_I(f) = \alpha'_H (I'_{gr})^2 / f N'_{eff}. \qquad (2.4)$$

Due both to the surface potential jump 2U and the 1/f noise of the spreading resistance, the surface recombination current will be noisier than an equal bulk recombination current, and this is in agreement with the experimental data[1,2].

(c) Injection - extraction quantum 1/f noise[6], due to injection or extraction of carriers across barriers. In this case, for not too small currents

$$S_I(f) = \alpha_{Hni} |I| q / f\tau;$$

$$\alpha_{Hni} = (4\alpha/3\pi)\left[2q(V_{dif}-V)+3kT\right]/m_n{}^*c^2, \tag{2.5}$$

where I is the injected current, and τ is the time of passage of a carrier through the barrier region. Introducing again an effective carrier number $N_{eff} = I\tau/q$, Eq. (2.5) may be written in a more general form, valid also for very small I

$$S_I(f) = \alpha_{Hni} I^2/fN_{eff}. \tag{2.5a}$$

Note that in each case N_{eff}, as long as it is larger than 1, is proportional to I (otherwise $N_{eff} \approx 1$, see below), and that α_H depends on bias.

(d) Recombination in the p region of a long n^+-p diode of length $W >> (D_n\tau_n)^{1/2}$ yields, as shown in Sec. III.3, Eqs. (3.15)-(3.19) on pp. 30-31,

$$S_I(f) = \alpha_{Hnr} |I| qF(a)/f\tau_n = \alpha_{Hnr} I^2/fN_{eff}; \tag{2.6}$$

$$N_{eff} = |I|\tau_n/qF(a), \quad \alpha_{Hnr} = (4\alpha/3\pi)\left[3kT/m_n{}^*c^2\right], \tag{2.6a}$$

Here F(a) is given by Eq. (3.14) of Sec. III.3, p. 30 below

$$F(a) = 1/3 - 1/2a + 1/a^2 - (1/a^3)\ln(1+a), \tag{2.7}$$

where

$$a = \exp(eV/kT) - 1. \tag{2.8}$$

In this case α_H is very small. Therefore this contribution will often be masked by mobility fluctuation 1/f noise.

(e) Recombination quantum 1/f noise at the p - region contact. The carriers lose an average energy 3kT/2 in the conduction band in the recombination process, gain an energy of the order of qE_g due to energy differences of the order of the band gap E_g accelerating the carriers at the contact surface, and gain an average energy 3kT/2 in the valence band, so that

$$\alpha_{Hnc} = (4\alpha/3\pi)\left[(2qE_g + 3kT)/m_n{}^*c^2\right]. \quad (2.9)$$

This effect will be important in short diodes ($W_p < L$), where the recombination speed at the contact patially determines the current through the device.

(f) Quantum 1/f noise in the tunneling rate. Tunneling is observed in n^+-p dioodes with sufficient gate bias[2]. If we assume that the momentum change of the carriers in the tunneling process is of the order of the thermal r.m.s. momentum, we obtain a minimal quantum 1/f noise power spectrum

$$S_I(f) = \alpha_H I^2/fN_{eff}; \quad N_{eff} = |I|\tau/q, \quad (2.10)$$

$$\alpha_H = (4\alpha/3\pi)\ 3kT/m_n{}^*c^2 \ , \quad (2.11)$$

where τ is the time of passage through the barrier, or tunneling, i.e. the time during which each carrie. contributes to the current through the barrier. Since the width of the barrier crossed by tunneling is small, this time is very short, of the order of 10^{-14}s. N_{eff} will then become larger than 1 at currents exceeding 10^{-5}A, leading to a linear current dependence of the noise power. At lower bias N_{eff} must be set equal to unity in Eq. (2.10). and this gives a quadratic current dependance. On the other hand, at large applied voltages, or for tunneling out of a metal, kT has to be replaced by a larger energy in the expression of α_H.

(g) Mobility fluctuation 1/f noise in a long n+-p diode. Although characterized mainly by a well defined momentum transfer of the carriers rather than by an effective energy, and although we have discussed it already above, this important process is listed here again. As shown in Sec.III.3, p.30, this contribution can be written in the form

$$S_I(f) = \alpha_H |I| qF(a)/f\tau_n = \alpha_H I^2/fN_{eff}; \quad N_{eff} = |I|\tau/qF(a), \quad (2.12)$$

where α_H is given by

$$\alpha_H = (4\alpha/3\pi)\left[\hbar/m^* ac\right]^2 \exp(-\theta_D/2T) + (4\alpha/3\pi)\left[6KT/mc^2\right] \quad (2.13)$$

for small devices, and is usually larger than in the case (d), particularly if the effective mass of the carriers is small. Here θ_D is the Debye temperature, a the lattice constant, and T the temperature. The first term in Eq. (2.13) is from umKlapp and inter - valley lattice scattering, while the second describes normal scattering processes. The function F(a) is again given by Eq. (2.7). In general this contribution includes umKlapp scattering, intervalley scattering, normal (non - UmKlapp) phonon scattering, impurity scattering, and optical phonon scattering contributions in the quantum 1/f mobility fluctuation Hooge parameter α_μ. For large samples or devices, Eq. (1.2) is applicable. Eq. (1.4) is a suggestion for the transition region.

II.2 DISCUSSION AND RECOMMENDATIONS

The quantum 1/f noise formulae presented above have been applied by Radford and Jones[2] to 1/f noise in GR, diffusion and tunneling currents in both double epitaxial layer and ion implanted n^+-p HgCdTe diodes. They obtained good agreement with the experimental data in general, but were a factor 20 below the measured values at positive gate bias, when an inversion layer formed at the surface. This discrepancy may be due both to the presence at positive gate bias of a noisy surface GR contribution (Eqs. 2.3-2.4), and to kinetic energies of the tunneling carriers above the thermal level in the vicinity of the inversion layer.

Another previously unexplained fact noted was the difference in the fractional noise level of surface and bulk recombination currents. This is caused in Eqs. (2.3-2.4) both by the surface potential jump 2U of the order of 1 Volt present at the interface between the bulk and the oxide and passivation layers, and by the quantum 1/f mobility fluctuation noise in the spreading resistance which affects the passage of carriers to and from the perimeter of the junction. Furthermore, the higher noise level of ZnS - passivated diodes may be caused by a larger surface recombination speed associated with these coatings compared to SiO_2 passivations, and by a larger effective value of U. The larger surface recombination speed pulls more of the recombination current from the bulk to the surface where it has higher fractional noise. The larger potential jump U increases the applicable Hooge parameter according to Eq. (2.3). Finally, the larger fractional 1/f noise levels of ion implanted junctions is mainly caused by the 1-2 orders of magnitude lower carrier lifetimes in Eqs. (2.2-2.13), which yield 1-2 orders of magnitude smaller N_{eff} values and larger fractional noise power values by the same factor.

In order to reduce the fractional noise level, the theory suggests the use of a surface passivation which lowers the surface recombination speed and the surface potential jump. The ideal "surface" would be a gradual increase of the gap width starting from the bulk through compositional changes leading to a completely insulating stable surface outwards, without the generation of surface recombination centers. In addition, the life time of the carriers should be kept high, and abrupt or pinched regions in the junction should be avoided. The reasonable choice of other junction parameters, including the steepness of the junction and the geometry should yield lower injection - extraction and bulk recombination noises by emphasizing the presence of the larger hole masses in the denominators of the above expressions. Finally, coherent state 1/f noise should be avoided by all means by optimizing the dimensions.

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II.3 REFERENCES

1. S.P.Tobin, S. Iwasa and T.J. Tredwell, IEEE-ED 27, 43 (1980).
2. W.A. Radford and C.E. Jones, J. Vac. Sci. Technol. A 3, 183 (1985).
3. J. Bajaj, G.M. Williams, M.H. Sheng, M. Hinnrichs, D.T. Cheung, J.P. Rode and W.E. Tennant, J. Vac. Sci. Technol. A 3, 192 (1985).
4. T.G.M. Kleinpenning, J. Vac. Sci. Technol. A 3, 176 (1985).
5. H.K. Chung, M.A. Rosenberg and P.H. Zimmermann, J. Vac. Sci. Technol. A 3, 189 (1985).
6. A. van der Ziel and P.H. Handel, IEEE-ED 32, 1802 (1985).
7. P.H. Handel, Phys Rev. Lett. 34, 1492, 1495 (1975).
8. P.H. Handel, Phys. Rev. A 22 745 (1980).
9. T.S. Sherif and P.H. Handel, Phys. Rev. A 26, 596 (1982).
10. P.H. Handel and D. Wolf, Phys. Rev. A 26, 3727 (1982).
11. P.H. Handel, Noise in Physical Systems and 1/f Noise edited by M. Savelli, G. Lecoy and J.P. Nougier (North Holland, 1983), p. 97.
12. P.H. Handel, Proc. VIII. Int. Conf on Noise in Physical Systems and 1/f Noise, Rome, 1985, to be published.
13. A. van der Ziel, Proc. VIII. Int. Conf on Noise in Physical Systems and 1/f Noise, Rome, 1985, to be published.
14. C.M. van Vliet and G.S. Kousik, Proc. VIII. Int. Conf on Noise in Physical Systems and 1/f Noise, Rome, 1985, to be published.
15. A. van der Ziel, P.H. Handel, X.C. Zhu and K.H. Duh, IEEE-ED 32, 667 (1985).

16. A. van der Ziel and J.B. Anderson, Proc. VIII. Int. Conf on Noise in Physical Systems and 1/f Noise, Rome, 1985, to be published.

17. P.H. Handel, Very low Frequency Quantum Electronics, 1/f Noise and Infra Quantum Physics ONR final Technical Report N00014-79-0405 (1982).

18. K.H. Duh and A. van der Ziel, IEEE-ED 32, 662 (1985).

19. A. Pavlikiewicz and A. van der Ziel, IEEE Electron Devices Letters, October 1985 issue.

20. F.N. Hooge, Phys. Lett. A 29, 139 (1969).

21. A.L. McWhorter, MIT Lincoln Lab. Rept. No.80 (1955).

22. W.H. Fonger in Transistors I, RCA labs, Princeton, NJ, (1956).

23. X.C. Zhu and A. van der Ziel, IEEE-ED 32, 658 (1985).

24. X.L. Wu and A. van der Ziel, Proc. VIII. Int. Conf on Noise in Physical Systems and 1/f Noise, Rome, 1985, to be published.

25. X.C. Zhu, X.L. Wu, A. van der Ziel and E.G. Kelso, IEEE-ED 32, 1353 (1985).

III. APPLICATION OF THE QUANTUM THEORY OF 1/f NOISE TO MIS INFRARED DETECTOR STRUCTURES

III.1 INTRODUCTION

The quantum 1/f noise theory is applied to the calculation of 1/f noise in the various dark current components which limit the performance of MIS Infrared detectors. The diffusion current transports minority carriers from the bulk to the surface inversion layer and is affected by coherent states quantum 1/f noise in the mobility, as long as the device is larger than approximately $10\mu m^2$ in area. For smaller devices we expect the smaller conventional quantum 1/f noise of the scattering cross sections to be expressed in the mobility and diffusion fluctuations. Quantum 1/f recombination speed fluctuations appear as fluctuations in the thermally generated current of minority carriers both at the surface and in the depletion region, which are majority carriers in the inversion layer. The rate of tunneling also presents quantum 1/f fluctuations which are calculated both for band to band tunneling and for tunneling via bandgap states, with the help of the same fundamental quantum 1/f formula used for the diffusion and recombination currents. Conventional quantum 1/f contributions are smaller for holes than for electrons, because they are inversely proportional to the effective mass.

III.2 CURRENTS IN MIS DETECTOR STRUCTURES

MIS detectors[9] are different from photovoltaic detectors, because they do not contain a pn junction obtained by inhomogeneous doping, and use an insulated field plate, or gate, placed on top of a homogeneously doped narrow - bandgap semiconductor. The gate is used to control the surface potential, driving the semiconductor surface into deep inversion. The field of the induced quasi - pn junction obtained under the surface of the gate in the homogeneous semiconductor material is used to separate the carriers generated by photo electrically induced band to band transitions just as in a photovoltaic device. The MIS infrared detector is therefore similar to a capacitively coupled photovoltaic detector, without the inconvenience of inhomogeneous doping processes.

MIS detectors are operated in the pulsed regime by applying the gate potential which creates the inversion under the surface for a finite time only, and by applying subsequently a potential which flattens the energy bands near the surface and releases the carriers which had accumulated from photo electric effect and dark current processes during the preceeding interval. The electrical signal obtained when the carriers are released, i.e., during readout, is proportional to the number of carriers accumulated, and therefore to the total current supplying the inverted volume under the surface with minority carriers from the bulk and from various thermal and photo electric processes in the depletion, inversion and surface regions. This electrical signal is used in order to determine the flux of infrared radiation. For this determination, however, the dark current contribution needs to be subtracted first.

The dark current is the current supplying the potential well, defined by the inversion region under the surface, with minority carriers in the absence of the applied infrared flux. Any low - frequency fluctuation in the dark current will be interpreted as a fluctuation in the major infrared flux signal. Therefore fluctuations of the dark current at frequencies below the readout frequency will limit the performance of infrared detectors. In the pulsed mode of operation considered here, the dark current is monitored only during the inverted phase, when carriers are accumulated in the potential well. Therefore the cross sections and process rates which control the intensity of the dark current are not observed continuously either. Nevertheless, the quantum 1/f fluctuations of these cross sections and process rates will be the same as if we would have observed them continuously. Indeed, the changes in the incoming flux of electrons testing all cross sections and process rates in the semiconductor is only slightly affected by the applied gate voltages, and is present also in thermal equilibrium. This independence of 1/f noise on the continuous or discontinuous character of any applied bias has been experimentally verified[16] during the last 2 decades, and *has been found to be in agreement with the interpretation of 1/f noise in terms* of fundamental resistance fluctuations. Although the experimental verification was performed on fluctuations in conduction only, from the concept of quantum 1/f noise we know that the similarity of quantum 1/f noise in the continuous and pulsed regimes should be also true for quantum 1/f fluctuations in recombination cross sections and tunneling rates.

The dark current has to be subtracted from the total current in a (HgCd)Te MIS device to yield the photocurrent. Therefore, the minority - carrier dark current is the single most important parameter for the operation of MIS devices as detectors infrared radiation[9]. This applies both to operation of MIS devices in the thermal equilibrium mode, in which the dark current determines the MIS diode impedance, and to operation in the dynamic, or integrating mode, in which the gate voltage is pulsed, and in which the minority - carrier dark current determines the storage time of the device. The main component of the dark current in narrow bandgap HgCdTe is the tunneling current via bandgap states[9], which can also be considered as an electric breakdown effect. In general, the tunneling current occurs both through band to band transitions and through intermediary states. The band to band tunneling current through a simple triangular barrier is

$$J_{tb} = (q^3 E \Phi_s / 4\pi^3 h^2)(2m^*/E_g)^{1/2} \exp\left[4(2m^*)E_g^{3/2}/3qhE\right], \quad (2.1)$$

where E is the electric field associated with the barrier, and E_g is the bandgap. The electric field can be approximated by the electric field at the semiconductor surface

$$E = (2qn_o \Phi_s / \varepsilon \varepsilon_o)^{1/2}, \quad (2.2)$$

where Φ_s represents the empty well surface potential, and n_o is the doping concentration. Substituting this value into Eq. (2), with $m^*/m_o = 7 \cdot 10^{-2} E_g$, we obtain[9]

$$J_{tb} = 10^{-2} n_o^{1/2} \Phi_s^{3/2} \exp\left[-4.3\ 10^{10} E_g^2/(n_o \Phi_s)^{1/2}\right] \mathrm{A/cm^2}, \quad (2.3)$$

where n_o is in cm^{-3} and E_g, Φ_s in volts. Therefore the tunneling current is strongly dependent on the bandgap and also depends on the doping concentration and the surface potential.

Experimental values of the tunneling current are usually larger than Eq. (2.3) because of the additional effect of tunneling via bandgap states. This effect is particularly important in n - type devices[10]. Indeed, in n - type devices the applied gate voltage is negative in order to produce depletion at the surface. The energy bands are therefore curved upwards at the surface, and transitions of electrons from the valence band to Shockley - Read (SR) states at the middle of the bandgap, as well as the subsequent transitions from these states to the conduction band are facilitated by the presence of many defects right at the surface of the semiconductor. In p - type devices the similar indirect tunneling processes occur father away from the surface, because in this case the bands are curved downwards at the surface, and transitions of electrons from the valence band to the centers at the middle of the bandgap, as well as the transitions from the centers to the conduction band well at the surface, occur right where the curvature begins, i.e., further away from the surface. We conclude that in p - type devices there will be fewer SR centers active in indirect tunneling, and therefore the tunneling current J_c via SR centers at a given teperature and a given applied gate voltage will be smaller. The tunneling current will be further reduced in p - type devices due to the lower density of states present in the surface potential well due to quantization of the motion of the electrons in the potential well at the surface. The reduced values of the dark current in p - type devices correspond to higher values of the breakdown field in these devices. The best measured value[10] of the breakdown field in 10 μm cutoff p - type devices is in exess of 1.0 V/μm, whereas that for n - type material of similar bulk defect quality is 0.5 V/μm. On the other hand, the minority carriers diffusion current is larger in p - type devices due to the smaller mass and higher diffusion constant of electrons compared to holes. The advantage of p - type devices is therefore considerable only in the case of very narrow bandgap and very long cutoff wavelengths. We shall therefore consider both the case of p - type and n - type devices. The large diffusion current present in p - type devices corresponds to the large value of the diffusion length of electrons and can be reduced by thinning the device, i.e., by reducing its thickness well below the diffusion length.

In general the dark current J_d can be written in the form

$$J_d = J_{diff} + J_{dep} + J_s + J_{tb} + J_{tc} + J_{tsc} + J_b + q\eta\phi_B \qquad (2.4)$$

The eight terms on the right hand side correspond to minority carrier diffusion from the bulk, generation from SR centers in the depletion region, generation from SR centers at the surface, band to band tunneling, tunneling via SR centers, tunneling via surface centers, recombination on the back surface and photoelectric generation by the thermal radiation background flux ϕ_B. We shall give the formulae[10] which determine these terms below, also including an example of their calculation in a p - type device

$$J_{dif} = (qn_i^2/p_o)\left[kT\mu_n/q\tau_n\right]^{1/2} = (1.6\ 10^{-19}C\cdot 36\cdot 10^{24}\ cm^{-6}/10^{15}cm^{-3})\left[0.01V\ 1.5\ 10^5(cm^2/Vs)/10^{-6}s\right]^{1/2} = 2\ 10^{-4}A/cm^2, \quad (2.5)$$

$$J_{depl} = qn_iW/2\tau_o = \left[(1.6\ 10^{-19}C\ 6\ 10^{12}cm^{-3}\ 2\ 10^{-4}cm\ /(2\ 10^{-6}s)\right] = 10^{-4}A/cm^2 \quad (2.6)$$

$$J_s = J_b = qn_is/2 = A(1.6\ 10^{-19}C\ 6\ 10^{12}cm^{-3}\ 20cm/s) = 1.8\ 10^{-5}A/cm^2, \quad (2.7)$$

$$J_{tc} = 10^{-13}(N_r\phi_S/E_g)\exp\left[-5.3\ 10^6E_g^2/E\right] = 10^{-13}(4\ 10^{12}cm^{-3}0.2V/0.062V)\exp\left[-5.3\ 10^6(0.062V)^2/3000V/cm\right] = 8\cdot 10^{-4}A/cm^2, \quad (2.8)$$

and J_{tb} was given by Eq. (2.3), yielding $10^{-7}A/cm^2$. Here $n_i = 6\ 10^{12}cm^{-3}$ is the intrinsic carrier concentration, and the concentration of holes was taken to be $p_o = 10^{15}cm^{-3}$. The mobility $\mu_n = 1.5\ 10^{15}cm^2/Vs$ as well as the life time $\tau_n = 10^{-6}s$ of the minority carriers have to be replaced by μ_p and τ_p for the case of n - type devices. The surface recombination speed was denoted by $s = 40cm/s$, and the concentration of intermediary states effective for tunneling was denoted by $N_r = 4\cdot 10^{12}cm^{-3}$. The bandgap considered was $E_g = 0.065eV$, the surface potential $\phi_S = 0.2V$ and the electric field below the surface $E = 3000V/cm$. All numerical values have been included only as an example and are not characteristic of a particular device. The numerical factors in Eq. (2.8) correspond to p - type HgCdTe with a $20\mu m$ cutoff wavelength and were taken from the paper of Kinch and Beck[10]. For n - type devices we also need to include tunneling via surface states. If the density of fast surface states is denoted by $N_{fs} = 10^{12}\ cm^{-2}V^{-1}$, the current generated from tunneling via a uniform density of fast surface states across the bandgap will be given by[9]

$$J_{tsc} = -q\xi p_1 N_{fs} KT/2q = 1.75\ 10^{-4}\ A/cm^2. \qquad (2.9)$$

The sum of the first seven currents on the right hand side of Eq. (2.4) must be smaller than the eighth which corresponds to the thermal radiation background flux, for background limited (BLIP) operation. Although not all terms in the dark current are of importance, we still retain them at this point, because their quantum 1/f noise may be quite significant, even if the corresponding current is negligible. We shall now proceed with the calculation of quantum 1/f noise contributions from all these currents.

III.3 QUANTUM 1/f NOISE SOURCES

1. 1/f Noise in the Diffusion Current

The diffusion limited dark current J_{diff} will exhibit 1/f noise due to conventional quantum 1/f fluctuations in the scattering cross sections of the carriers due to phonons and impurities. We apply the fundamental formula given by Eq. (1.1) for an individual scattering process in which the velocity change $\Delta\vec{v}$ is given by the thermal energy of the carriers, with the assumption that the collisions are perfectly randomizing collisions. If the velocity $\vec{v}$ is rotated by an angle θ in an elastic collision, the velocity change is $|\Delta\vec{v}| = 2v \sin(\theta/2)$. Averaging over all angles and velocities, we obtain

$$\Delta\vec{v}^2 = 4\overline{v^2}\ \overline{\sin^2(\theta/2)} = 2\overline{v^2}, \qquad (3.1)$$

and therefore from Eq. (1.1) we get in thermal equilibrium at the temperature T the 1/f noise coefficient

$$\alpha_H = (4\alpha/3\pi)(6KT/m^*c^2), \qquad (3.2)$$

where we have assumed a Maxwell distribution of velocities. For $Hg_{1-x}Cd_xTe$ with $x = 0.2$ we have $m_n^* = 0.008m_o$ and for $x = 0.3$ we have $m_n^* = 0.02m_o$. Therefore we obtain $\alpha_H = 2\ 10^{-7}$ in the first case and $\alpha_H = 7.5\ 10^{-8}$ in the second case.

For the case of Umklapp scattering, which occurs in semiconductors only to a limited extent due to the relatively small number of high momentum phonons available at the temperature T, the momentum change of the electron is given by the smallest reciprocal lattice vector, and therefore $\Delta v = h/am^*$. We therefore obtain the quantum 1/f noise coefficient

$$\alpha_H = (4\alpha/3\pi)(h/m^*ac)^2, \qquad (3.3)$$

which is much larger than Eq. (3.2), but has to be multiplied with a negative exponential which describes the scarcity of phonons with momentum of the order of a reciprocal lattice vector. [The negative exponential $e^{-\theta/T}$ could be included in the current weight factor which will be defined below in Eq. (4.3), but we prefer to include it here already]. Combining Eqs. (3.2) and (3.3), we obtain for conventional 1/f noise in the mobility and diffusion coefficients

$$\alpha_H = (4\alpha/3\pi)[(6kT/m^*c^2) + (h/m^*ac)^2 \exp(-\theta/T)], \qquad (3.4)$$

where θ is about half the Debye temperature for simple metals, but may be higher, of the order of the Debye temperature, for semiconductors.

The quantum 1/f noise considered so far is known as conventional quantum 1/f noise, and affects cross sections and process rates. In sufficiently large semiconductors samples we expect a larger form of quantum 1/f noise, described in Appendix A and known as coherent state quantum 1/f noise. For this type the 1/f noise coefficient is given by

$$\alpha_{coh} = 2\alpha/\pi = 4.6\ 10^{-3}. \qquad (3.5)$$

The values of the quantum 1/f noise coefficient given by Eqs. (3.1) - (3.5) can be used to calculate the quantum 1/f noise which affects the various currents listed in Eq. (2.4). We first consider the case of the dark diffusion current of electrons from the bulk through the surface barrier in a p-type MIS device, similar to diffusion in a n^+p junction, because in both cases the current is determined by the diffusion of electrons which are minority carriers, against the built - in field of a Boltzmann potential barrier into the surface well, and by the thermal generation of carriers there. We start with the derivation of the mobility fluctuation part of quantum 1/f noise in a n^+-p diode. For the MIS barrier, just as for a diffusion limitted n^+-p junction, the current is controlled by diffusion of electrons into the p - region over a distance of the order of the diffusion length $L = (D_n \tau_n)^{1/2}$ which is usually shorter than the length w_p of the p - region. If N(x) is the number of electrons per unit length and D_n their diffusion constant, the electron current at x is

$$I_{nd} = -eD_n dN/dx, \qquad (3.6)$$

where we have assumed a planar junction and taken the origin x = 0 in the junction plane. Diffusion constant fluctuations, given by KT/e times the mobility fluctuations, will lead to local current fluctuations in the interval Δx

$$\delta I_{nd}(x,t) = I_{nd}\delta D_n(x,t)/D_n. \qquad (3.7)$$

The normalized weight with which these local fluctuations representative of the interval Δx contribute to the total current I_d through the diode at x = 0 is determined by the appropriate Green function and can be shown to be $(\Delta x/L)\exp(-x/L)$ for $w_p/L >> 1$. Therefore the contribution of the section Δx is

$$\delta\Delta I_d(x,t) = (\Delta x/L)\exp(-x/L) I_{nd}\delta D_n(x,t)/D_n, \qquad (3.8)$$

with the spectral density

$$S_{\Delta Id}(x,f) = (\Delta x/L)^2 \exp(-2x/L)\, I_{nd}^2\, S_{Dn}(x,f)/D_n^2. \qquad (3.9)$$

For mobility and diffusion fluctuations the fractional spectral density is given by $\alpha_{Hnd}/fN\Delta x$, where α_{Hnd} is determined from quantum 1/f theory according to Eqs. (3.1) -(3.5). With Eq. (3.6) we obtain then

$$S_{\Delta Id}(x,f) = (\Delta x/L^2)\exp(-2x/L)\,(eD_n dN/dx)^2 \alpha_{Hnd}/fN. \qquad (3.10)$$

The electrons are distributed according to the solution of the diffusion equation, i.e.

$$N(x) = [N(0) - N_p] \exp(-x/L) + N_p; \quad dN/dx = -\{[N(0) - N_p]/L\} \exp(-x/L). \quad (3.11)$$

Substituting into Eq. (3.10) and simply summing over the uncorrelated contributions of all intervals Δx, we obtain

$$S_{Id}(f) = \alpha_{Hnd}(eD_n/L^2)^2 \int_0^{w_p} [N(0) - N_p]^2 e^{-4x/L} dx \,/\{[N(0) - N_p]e^{-x/L} + N_p\}. \quad (3.12)$$

We note that $(eD_n/L^2)^2 = (e/\tau_n)^2$. With the expression of the saturation current $I_0 = e(D_n/\tau_n)^{1/2}N_p$ and of the current $I = I_0[\exp(eV/kT) - 1]$ we can carry out the integration

$$S_{Id}(f) = \alpha_{Hnd}(eI/f\tau_n)\int_{e^{-w_p/L}}^{1} a^2u^3du \,/(au + 1)$$

$$= \alpha_{Hnd}(eI/f\tau_n)\,[F(a) - F(a\, e^{-w_p/L})] \simeq \alpha_{Hnd}(eI/f\tau_n)aw_p/[(a + 1)L], \quad (3.13)$$

the last form being for $w_p \ll L$. Here we have introduced the notations

$$u = \exp(-x/L), \quad a = \exp(eV/kT) - 1,$$

$$F(a) = 1/3 - 1/2a + 1/a^2 - (1/a^3)\ln(1+a). \quad (3.14)$$

For $w_p \gg L$ we have $F(o) = 0$, and the second term in rectangular brackets drops out in Eq. (3.13).

Eq. (3.13) only contains the fluctuations in the mobility and the diffusion constant. In a similar way we calculate the quantum 1/f fluctuations of the recombination rate in the bulk of the p - region. We have for the recombination current $\Delta I_R(x)$ in a section Δx, if $N'(x)$ is the excess carrier density,

$$\Delta I_R(x) = eN'(x)\Delta x/\tau_n \,. \quad (3.15)$$

Putting $C_n = 1/\tau_n$ and bearing in mind that τ_n, and hence C_n, fluctuates, we have for the section Δx,

$$\delta \Delta I_R(x, t) = \Delta I_R(x)[\delta C_n/C_n], \text{ with}$$

$$S_{Cn}(x,f)/C_n^2 = \alpha_{hnr}/f\Delta N \qquad (3.16)$$

so that, since $N(x) = \Delta N/\Delta x$,

$$S_{\Delta IR}(x,f) = \Delta I_R^2(x)[\alpha_{Hnr}/f\Delta N]$$

$$= \alpha_{Hnr}\{e^2[N'(x)]^2/f\tau_n^2 N(x)\}\Delta x, \qquad (3.17)$$

where $N'(x) = [N(0) - \ _p]\exp(-x/L)$ and $N(x) = N'(x) + N_p$ as before.

It is easily shown that the fluctuating current $\delta\Delta I(x,t)$ at the junction is

$$\delta\Delta I(x,t) = \delta\Delta I_R(x,t)\exp(-x/L) \qquad (3.18)$$

so

$$S_I(f) = \alpha_{Hnr}(e^2N_pL/f\tau_n^2)\int_0^{w_p}\{[N'(x)]^2/N_pN(x)\}\exp(-2x/L)d(x/L) =$$

$$\alpha_{Hnr}(eI_0/f\tau_n)\int_{\exp w_p/L}^{1}[a^2u^3/(au+1)]du = \alpha_{Hnr}[eI/f\tau_n][F(a) - F(ae^{-w/L})] \qquad (3.19)$$

where $F(a)$, a, and u have the same meaning as before.

We can use the similarity of the quantum 1/f noise results for diffusion current fluctuations caused by mobility fluctuations and by recombination speed fluctuations in order to combine both into a single formula

$$S_I(f) = (\alpha_{Hd} + \alpha_{Hnr})[eI/f\tau_n][F(a) - F(ae^{-w/L})]. \qquad (3.20)$$

In the limit of very short devices ($w_p \ll L$) the last factor becomes $aw/[(a+1)L]$, and in the limit of long MIS devices ($w_p \gg L$) it simply becomes $F(a)$. In addition we have a current noise contribution S_{Jb} from the quantum 1/f fluctuation of the recombination speed s on the back surface.

So far we have considered only conventional quantum 1/f noise which is applicable to sufficiently small devices. In general, however, we must interpolate between conventional and coherent quantum 1/f noise, according to the relation

$$\alpha_H = [1/(1+s)][2\ \ A/f] + [s/(1+s)][2\alpha/\pi f], \qquad (3.21)$$

where $s = E_m/E_K = 2e^2N'/m^*c^2$, and $N' = nS$ is the number of the carriers per unit length of the device. s represents the ratio between the magnetic energy per unit length and the kinetic energy per unit length of the device. The quantity $e^2/m^*c^2 = r_0 m/m^*$ can be calculated in terms of the classical radius of the electron $r_0 = 2.84\ 10^{-13}$ cm. Then we obtain $s = 2\ r_0 N'm/m^*$, i.e., the parameter s represents twice the number of carriers present in a length of the device equal to the classical radius of the electron. We must compare s with πA, and if $s \ll \pi A$ we apply conventional quantum $1/f$ noise, whereas for $s \gg \pi A$ we have to apply coherent quantum $1/f$ noise. In general the approximate formula of Eq. (3.21) must be used for the transition region.

The dimensionless parameter s is easy to calculate in any practical case. For instance in the case of a MIS device of area $50\mu m \times 50\mu m$ with a concentration of carriers of 10^{16} cm^{-3} we obtain $N' = 2.5\ 10^{11}$/cm, and with $m/m^* = 50$ we obtain $s = 7$. On the other hand, we can estimate A for conventional quantum $1/f$ noise and we will certainly find $A \ll 1$, because the velocity change of the carriers must be much smaller than the speed of light. Therefore, in this case we must apply coherent quantum $1/f$ noise, because $s \gg \pi A$. Consequently, in Eq. (3.20) we must set

$$\alpha_{Hd} + \alpha_{Hnr} = \alpha_{coh} = 4.6\ 10^{-3} \tag{3.22}$$

The coherent state quantum $1/f$ noise coefficient thus replaces the total conventional Hooge parameter.

2. 1/f Noise of the Recombination Current Generated in the Depletion Region

The quantum $1/f$ noise of the recombination current thermally generated in the depletion region arises from quantum $1/f$ fluctuations of the bulk recombination rates in the depletion region. The difference between the recombination rate R and the generation G is given by

$$R - G = [pn - n^2_i]/[(n + n_1)\tau_{po} + (p + p_1)\tau_{no}] \qquad (3.23)$$

where n_1 and p_1 are electron and hole densities when the Fermi level lies at the trap level. If the trap level lies at the intrinsic level, $n_1 = p_1 = n_i$. Moreover, τ_{po} and τ_{no} are time constants for electrons and holes. If A is the cross - sectional area of the junction, the current is

$$I = \int_0^w e(R - G)A\,dx = e\int_0^w [pn - n^2_i]/[(n + n_i)\tau_{po} + (p + n_i)\tau_{no}]A\,dx \qquad (3.24)$$

where w is the width of the space - charge region and the trap level is assumed to lie at the intrinstic level.

We now turn to the g - r noise. The time constants τ_{po} and τ_{no} fluctuate in a 1/f fashion and this produces the quantum 1/f contribution to g - r noise. We now write

$$\tau_{no} = 1/C_n$$

$$\tau_{po} = 1/C_p \qquad (3.25)$$

where C_n and C_p are the generation (or combination) rates for a single electron and for a single hole, respectively. Consequently

$$\delta\tau_{no}/\tau_{no} = -(\delta C_n/C_n)$$

$$\delta\tau_{po}/\tau_{po} = -(\delta C_p/C_p) \qquad (3.26)$$

We now apply this knowledge to Eq. (3.23) and observe that

$$\delta(R - G) = [R(x) - G(x)]$$

$$\{[(n + n_i)\tau_{po}(\delta C_p/C_p)] + [(p + p_i)\tau_{no}(\delta C_n/C_n)]\}/[(n + n_i)\tau_{po} + (p + n_i)\tau_{no}]. \quad (3.27)$$

so that with

$$\delta I = e \int_0^w \delta[R(x) - G(x)]A\,dx, \qquad (3.28)$$

the noise is

$$S_I(f) = e^2 \int_0^w \int_0^w [R(x) - G(x)]A[(R(x') - G(x')]A$$
$$\{[(n + n_i)^2 \tau_{po}{}^2 S_{Cp}(x, x', f)/C_p{}^2 + (p + n_i)^2 \tau_{no}{}^2 S_{Cn}(x, x', f)/C_n{}^2]$$
$$/[(n + n_i)\tau_{po} + (p + n_i)\tau_{no}]^2\}dx\,dx', \qquad (3.29)$$

since δC_p and δC_n are independent.

We now observe that

$$pn - n^2{}_i = n^2{}_i[\exp(eV/2KT) - 1][\exp(eV/2KT) + 1] \qquad (3.30)$$

and that the integrand in Eq. (3.29) has an appreciable value only if $p \simeq n \simeq n_i$ $\exp(eV/2KT)$. By substituting $n + n_i = p + n_i = n_i[\exp(eV/2KT) + 1]$ we define an effective width w_{eff} such that

$$eA \int_0^w [(pn - n^2{}_i)dx]/[(n + n_i)\tau_{po} + (p + n_i)\tau_{no}]$$
$$= eA\{(pn - n^2{}_i)/n_i[\exp(eV/2KT) + 1]\}[w_{eff}/(\tau_{po} + \tau_{no})] \qquad (3.31)$$

We may thus write

$$I = I_{gr} = eAw_{eff}n_i[\exp(eV/2KT) - 1]/(\tau_{po} + \tau_{no})$$
$$= [eN_{eff}/(\tau_{po} + \tau_{no})]\tanh eV/2KT \qquad (3.32)$$

where $N_{eff} = Aw_{eff}n_i[\exp(eV/2KT) + 1]$ is the effective number of hole - electron pairs taking part in the conduction and noise processes. This equation is exact but not very useful since it contains the unknown parameter w_{eff}.

We now turn to Eq. (3.29) and observe that

$$S_{Cp}(x, x', f)/C^2_p = \{(\alpha_{Hp}/f)/[R(x') + G(x')](\tau_{po} + \tau_{no})A\}\delta(x' - x) \quad (3.33)$$

and

$$S_{Cn}(x, x', f)/C^2_n = \{(\alpha_{Hn}/f)/[R(x') + G(x')](\tau_{po} + \tau_{no})A\}\delta(x' - x) \quad (3.34)$$

The factor $(\tau_{no} + \tau_{po})$ enters in because $S_{Cp}(x, x', f)/C^2_p$ and $S_{Cn}(x, x', f)/C^2_n$ must be independent of τ_{po} and τ_{no} if $p \simeq n \simeq n_i \exp(eV/2KT)$. This yields, if we integrate over the δ function

$$S_I(f) = e^2 \int_0^w \{[R(x) - G(x)]^2 A/(\tau_{po} + \tau_{no})[R(x) + G(x)]\}$$
$$\{[(n + n_i)^2 \tau_{po}^2 \alpha_{Hp}/f + (p + n_i)^2 \tau_{no}^2 \alpha_{Hn}/f]/[(n + n_i)\tau_{po} + (p + n_i)\tau_{no}]^2\}dx \quad (3.35)$$

We now observe that the second factor in Eq. (3.35) is practically a constant as long as p and n are comparable. We may thus bring that factor outside the integral sign and write

$$[(n + n_i)^2 \tau_{po}^2 \alpha_{Hp}/f + (p + n_i)^2 \tau_{no}^2 \alpha_{Hn}/f]$$
$$/[(n + n_i)\tau_{po} + (p + n_i)\tau_{no}]^2 = \alpha_H/f, \quad (3.36)$$

where α_H is given by

$$\alpha_H = (\tau_{po}/\tau_{po} + \tau_{no})^2 \alpha_{Hp} + (\tau_{no}/\tau_{po} + \tau_{no})^2 \alpha_{Hn} \quad (3.37)$$

We thus have

$$S_I(f) = [\alpha_{He}/f(\tau_{no} + \tau_{po})] \cdot e \int_0^w [R(x) - G(x)]^2 A/[R(x) + G(x)]dx$$
$$= [\alpha_{He} I_{gr}/f(\tau_{no} + \tau_{po})]\tanh[eV/2KT] \quad (3.38)$$

We can now prove Eq.(3.38) in a Hooge - type formulation [1].

Here we put

$$S_I(f)/I^2_{gr} = \alpha_H/fN_{eff} \quad (3.39)$$

But according to Eq.(3.32), $I_{gr} = (eN_{eff}/\tau)\tanh eV/2KT$, so that

$$S_I(f) = \alpha_H[eI_{gr}/f\tau]\tanh eV/2KT, \quad \tau = (\tau_{no} + \tau_{po}) \qquad (3.40)$$

in agreement with Eq.(3.38).

We can also prove Eq.(3.38) from the following consideration. We write $I_{gr} = (N_{eff}\Delta I)\tanh eV/2KT$, where $\Delta I = e/\tau$ fluctuates. We then have

$$S_{\Delta I}(f)/\Delta I^2 = \alpha_H/f \text{ or } S_{\Delta I}(f) = \alpha_H/f(e/\tau)\Delta I \qquad (3.41)$$

so that, since the N_{eff} hole - electron pairs are independent

$$S_I(f) = N_{eff}S_{\Delta I}(f) = (eN_{eff}\Delta I/f\tau)\alpha_H = [(eI_{gr}/f\tau)\alpha_H]\tanh ev/2KT \qquad (3.42)$$

where α_H is given by Eq.(3.37) and $\tau = (\tau_{no} + \tau_{po})$.

The last two approaches are easily extended to other cases; the method works as long as a time constant τ and an N_{eff} can be defined.

We finally evaluated α_{Hp} and α_{Hn} from quantum 1/f noise considerations [2], [3].

$$\alpha_{Hn} = (4\alpha/3\pi)(\overline{\Delta v^2}_n/c^2) = 4\alpha/3\pi\{[2ea(V_{dif} - V) + 3KT]/m^*_n c^2\} \qquad (3.43)$$

$$\alpha_{Hp} = (4\alpha/3\pi)(\overline{\Delta v^2}_p/c^2) = 4\alpha/3\pi[2e(1 - a)(V_{dif} - V) + 3KT]/m^*_p c^2] \qquad (3.44)$$

and as a consequence (see Eq.(3.37) and

$$\alpha_H = (4\alpha/3\pi)\{[2e(V_{dif} - V) + 6KT]/[(m^*_n)^{1/2} + (m^*_p)^{1/2}]^2c^2 \qquad (3.45)$$

The problem has hereby been solved. Note that in $Hg_{1-x}CD_xTe$ with $x = 0.3$, $m^*_n = 0.02$ m, $m^*_p = 0.55$ m, so that $[(m^*_n)^{1/2} + (m^*_p)^{1/2}]^2 = 0.78$ m, very much larger than m^*_n.

3. Noise in the Surface Recombination Current

The surface recombination currnet is a dark current component originating from surface states at the interface between the surface passivation layer and the bulk. The recombination cross sections of these states will exhibit quantum 1/f noise. The quantum 1/f noise coefficient α_H reflects the velocity change of carriers involved in this process

$$\alpha_H = (4\alpha/3\pi)(2/m^*c^2)[3KT/2 + eU/2 + 0.1eV], \qquad (3.46)$$

where U is the surface potential jump present between the surface passivation layer and the bulk even if no gate voltage is applied, and V is the applied gate voltage which we take with a coefficient less than unity, here for example with a weight of 0.1.

The calculation of surface recombination quantum 1/f noise is similar to the calculation of quantum 1/f noise from recombination in the space charge region. However, in this case the cross sections are not distributed over the width of the junction, but rather are concentrated at the surface which is caracterized by the surface potential ϕ_S. Therefore we can write an expression of the form

$$S_{Js}(f) = \alpha_H e J_s \tanh x \,/ f(\tau_{no} + \tau_{po}) \exp(e\phi_s/KT). \qquad (3.47)$$

We note that the fabrication process of MIS structure introduces less bulk defects than the fabrication of photovoltaic devices. Nevertheless, the fabrication of MIS devices introduces some defects in the bulk layer located right under the surface. These defects will manifest themselves through a contribution to indirect tunneling.

4. Quantum 1/f Noise in the Tunneling Rate

In the case of tunneling from a surface accumulation layer to the bulk, the velocity change of the carriers will lead us from the thermal velocity of the carrier on one side of the barrier to the thermal velocity of a carrier on the other side of the barrier, if band to band tunneling is considered. If, however, the tunneling goes via intermediate states located in the bandgap, the velocity is zero as long as the carrier is stationary in the intermediate state. We can therefore write the 1/f noise coefficient

$$\alpha_H = (4\alpha/3\pi)6KT/m^*c^2 \qquad (3.48)$$

for band to band tunneling, and

$$\alpha_H = (4\alpha/3\pi)3KT/m^*c^2 \qquad (3.49)$$

for tunneling via intermediate states in the bandgap, where we have considered the average squared velocity change two times smaller. The effective mass is the mass of the minority carriers in the bulk material.

For band to band tunneling from a surface inversion layer to the bulk, the velocity change of carriers corresponds to an energy difference of the order of the bandgap E_g plus an energy differnce of the order of the thermal energy 3KT/2, provided we are dealing with deep inversion, as used in practical MIS devices in the pulsed mode of operation. This yields the quantum 1/f coefficient

$$\alpha_H = (4\alpha/3\pi)(E_g + 3KT/2)/m^*c^2 \qquad (3.50)$$

for band to band tunneling. For tunneling via intermediate states in the bandgap the corresponding energy differnce will be smaller, and therefore we replace E_g by $E_g/2$:

$$\alpha_H = (4\alpha/3\pi)(E_g/2 + 3KT/2)m^*c^2. \tag{3.51}$$

This relation is applicable both if the intermediate states are located in the depletion region or at the surface.

In the last four equations we did not divide by the number of carriers simultaneously involved in the tunneling process, because this number is less than unity for practical tunneling currents. Whenever a cross section or a process rate is tested with one electron or less than one electron at a time, the effective number of electrons in the denominator of the quantum 1/f formula must be replaced by unity. Let us calculate the average number of carriers simultaneously present in the tunneling process at any time. The tunneling process occurs over a distance $d = E_g/eE$, and the speed v of the carriers will be of the order of the thermal speed in the case of an accumulation layer, and of the order of the bandgap energy in the case of a surface inversion layer. Dividing d by v, we obtain a tunneling time $t = 6 \cdot 10^{-13}$s for accumulation layers and $t = 3 \cdot 10^{-13}$s for inversion layers. From Eq. (2.8) we know that the tunneling current is of the order of 10^{-3}A/cm^2. Multiplying this by t, we obtain $3 - 6 \cdot 10^{-16}$ C, i.e., 2000 – 3000 electrons/cm^2 tunneling simultaneously in a device of 1 cm^2 area. In a device of dimensions 50 μm x 50 μm = 2.5 10^{-5} cm^2 the average number of carriers in the process of tunneling at any time is therefore 0.05 – 0.075, and this is indeed much less than unity. Nevertheless, if the area of the device exceeds 5 10^{-4} cm^2, Eqs. (3.48) – (3.51) require an additional factor e/tJ_tA which makes the noise spectral density proportional to J_t and A, rather than to the square of these quantities.

The photoelectric current will reflect the fluctuations in the number of photons arriving from the radiation background. The quantum efficiency will not exhibit considerable quantum 1/f noise, because the generated carriers will be corrected with certainty. Therefore the collection of photoelectrically generated carriers is not controled by any cross section or process rate affected by considerable quantum 1/f noise. If we neglect the 1/f noise generated in the series resistance of the diode, there should be no photoelectrically generated 1/f noise from a short – circuited diode.

Since the various dark current fluctuations with 1/f spectrum are statistically independent, the total 1/f noise is simply obtained by summing all contributions.

III.4 1/f NOISE LIMITED PERFORMANCE OF MIS DIODES

From Eq. (2.4) we write the total dark current fluctuation in the form

$$\delta J_d = \delta J_{dif} + \delta J_{dep} + \delta J_s + \delta J_{tb} + \delta J_{tc} + \delta J_{tsc} + q\delta(\eta\phi_B), \quad (4.1)$$

and the spectral density of current fluctuations will be neglecting $\delta(\eta\phi_B)$,

$$S_{Jd} = S_{Jdif} + S_{Jdep} + S_{Js} + S_{Jtb} + S_{Jtc} + S_{Jtsc}. \quad (4.2)$$

Here we have lumped the recombination current on the back surface J_b together with the surface recombination (generation) current J_s. If we denote all the corresponding spectral densities of fractional fluctuations by a prime, $S'_{Ji} = S_{Ji}/J_i^2$, we obtain

$$S'_{Jd} = (J_{dif}/J_d)^2 S'_{dif} + (J_{dep}/J_d)^2 S'_{Jdep} + (J_s/J_d)^2 S'_{Js}$$
$$+ (J_{tb}/J_d)^2 S'_{Jtb} + (J_{tc}/J_d)^2 S'_{Jtc} + (J_{tsc}/J_d)^2 S'_{Jtsc}. \quad (4.3)$$

This equation was obtained by dividing the previous equation through J_d^2, and shows that the biggest contribution will not necessarily come from the process with the highest fractional quantum 1/f noise, i. e., with the highest 1/f noise coefficient. The weight of each type of noise is determined by the corresponding squared current ratio.

The detectivity of infrared detectors is limited in general by three types of noise: (i) curent noise in the detector, (ii) noise due to background photons (photon noise), (iii) noise in the electronic system following the detector. We shall neglect here the background photon noise and the noise in the electronic system. The detectivity is defined as

$$D^*(\lambda, f) = (A\Delta f)^{1/2}/NEP(cmHz^{1/2}/W) \tag{4.4}$$

where A is the area of the detector, NEP the noise equivalent power defined as the r.m.s. optical signal of wavelengh λ required to produce r.m.s. noise voltage (current) equal to the r.m.s. noise voltage (current) in a bandwidth Δf, and f is the frequency of modulation. The noise equivalent power NEP is given by

$$NEP = (h\nu/\eta q)(S_{Id}(f)\Delta f)^{1/2}. \tag{4.5}$$

Therefore we obtain for the detectivity

$$D^*(\lambda, f) = (\eta q\lambda/hc)\,[A/S_{Id}(f)]^{1/2} = (\eta q\lambda/hc)\,[S_{Jd}(f)]^{-1/2} \tag{4.6}$$

We notice that $D^*(\lambda, f)$ is proportional to λ up to the peak wavelength λ_c. For $\lambda > \lambda_c$ we have $\eta = 0$ and thus $D^*(\lambda, f) = 0$. By substituting our result for S_{Jd}, we obtain the general expression of the detectivity as a function of various parameters of the MIS device.

Let us now evaluate the magnitude of the various dark current noise contributions. With $m_h^* = 0.55\ m_o$, $m_n^* = 0.02\ m_o$, $\tau_n = 10^{-6}s$, $E_g = 0.1$ eV, $3KT/2 = 0.01$ eV, $N_{sf} = 10^{12}/Vcm^2$, we obtain for a p - type device with $w_p \gg L$

$$S'_{Jdiff} = (\alpha_{Hnd} + \alpha_{Hnr})[e/f\tau_n J_{diff}]F(a) = \alpha_{coh}\{e^{1/2}/[f(KT\mu\tau_n)^{1/2}N_p]\}F(a)/a$$
$$= (4.6\ 10^{-3}/4fN_p)\ 4\cdot10^{-10}C^{1/2}/[10^{-6}s\ 1.5\cdot10^5(cm^2/Vs)\ 4\cdot10^{-21}\ J]^{1/2}$$
$$= 1.8\cdot10^{-6}cm^2/f,\ [or = 10^{-8}\ cm^2/f, \text{ with } \alpha_{Hp} = 2\cdot10^{-5} \text{ for incoherent noise}] \tag{4.7}$$

$$S'_{Jdep} = [\alpha_{He}e/f(\tau_{no} + \tau_{po})J_{dep}]\tanh eV/2KT$$

$= [\alpha_{He} e/feAwn(eV/2KT)]eV/2KT = \alpha_{He}/fAwn_i = 4.6\ 10^{-9} cm^2/f$ (4.8)

$S'_{Js} = (4\alpha/3\pi)(2/m^*c^2)[3KT/2 + eU/2 + 0.1Ve]\ [e\ \tanh x\ /f(\tau_{no} + \tau_{po})J_s]$

$= (4\alpha/3\pi 0.02)(2/500000)[0.025 + 0.5 + 0.5]\ [e\ \tanh x\ /feAwn_i(e^{eV/2KT} - 1)]$

$= 7\ 10^{-8} cm^2/f$ (4.9)

$S'_{Jtb} = (4\alpha/3\pi)(E_g + 3KT/2)/m^*c^2 = (4/9.5\ 137\ 0.02)(0.11/500000)$

$= 3.3\ 10^{-8} cm^2/f$ (4.10)

$S'_{Jtc} = (4\alpha/3\pi)(E_g + 3KT)/2m^*c^2 = (4/9.5\ 137\ 0.02)(0.12/10^6)$

$= 1.8\ 10^{-8} cm^2/f = S'_{Jtsc}$ (4.11)

S'_{Jdiff} was calculated in the small bias limit for $w_p >> L$, but $w_p = 0.25$ L gives the same result; the incoherent case with a lattice constant of 0.65 nm and $\theta = 320$ K was also listed above (because a 10 μm thick device is very short, so it may be applicable), and would give $1.8\ 10^{-10} cm^2/f$ for a n - type device. Eqs. (4.8) - (4.11) would be reduced only $m_p^*/m_n^* = 27.5$ times for n - type devices. We mention that S'_{Js} has been calculated with the inclusion of a term of 10% of the applied gate voltage V into the kinetic energy of the carriers at the surface, and that for the back surface recombinaiton current this term has to be dropped in the similar expression of S'_{Jb}. However, we have neglected this here, because the surface recombination terms will not turn out to be important, as we will see below. The applied gate voltage was taken to be V = 5 V. Using Eq. (4.3) and the current densities evaluated in Eqs. (4.10) - (4.14) to calculate the fraction of each current, we obtain

$1\ cm^{-2}\ f\ S'_J(f) = (20/132)^2\ 1.8\ 10^{-6} + (10/132)^2\ 4.6\ 10^{-9} + (3.6/132)^2\ 7\ 10^{-8} +$
$(0.01/132)^2\ 3.3\ 10^{-8} + (80/132)^2\ 1.8\ 10^{-8} + (17.5/132)^2\ 1.8\ 10^{-8}$
$= 3.67\ 10^{-8} + 2.6\ 10^{-11} + 5.2\ 10^{-11} + 1.9\ 10^{-16} + 6.61\ 10^{-9} + 3.17\ 10^{-10}$
$= 4.37\ 10^{-8}$, or for incoherent 1/f noise, $7.1\ 10^{-9}$ (p) and $3\ 10^{-10}$ (n). (4.12)

This value can be used in order to estimate the detectivity of the device in our example. Substituting into Eq. (4.6), we obtain with a quantum efficiency $\eta = 0.7$ and wavelength of 10μm

$D^*(\lambda, f) = (\eta q\lambda/hc)\,[S_{J_d}(f)]^{-1/2} = [0.7\cdot 1.6\cdot 10^{-19}C\; 10^{-5}m/(6.6\cdot 10^{-34}Js\; 3\cdot 10^8 m/s)]\,[f/(4.37\cdot 10^{-8}cm^2\; 1.74\cdot 10^{-6}A^2/cm^4)]^{1/2} = 2\cdot 10^7\,(cm\,Hz^{1/2}/w)\,f^{1/2}$, or for incoherent 1/f noise, $5\cdot 10^7$ (p), and $2.5\; 10^8$ (n). (4.13)

In conclusion we note that for the relatively large devices which we have considered, most of the quantum 1/f noise comes from fluctuations in diffusion and in the tunneling rate via impurity centers in the bandgap. The effective mass of the carriers is present in the denominator of all quantum 1/f noise contributions except the coherent quantum 1/f fluctuation present in the diffusion current of large devices. In smaller devices the diffusion current will also be given by the conventional quantum 1/f formula which contains the effective mass of the carriers in the denominator. For umklapp scattering the mass of the carriers in the denominator is even squared. Consequently we expect lower quantum 1/f noise from n - type devices, in which the minority carriers are holes, particularly if the devices are very small, e.g., below 10μm.

III.5 DISCUSSION AND RECOMMENDATIONS

The transition from coherent state quantum 1/f noise to conventional quantum 1/f noise is particularly interesting, and should be studied experimentally. This is possible with a sequence of devices of smaller and smaller size, and will show a consideralble change in noise at a size of the order of 10μm^2. The theory of the transition is not yet well developed. Therefore, this experiment has particular importance; we do not know if the parameter s is sufficient to characterize the transission, and if the parameter s should not be replaced by a power of s, or by any other function of s. The interpolation formula used here is just a guess, or a speculation guided by the physical understanding of coherent quantum 1/f noise as a collective-field effect, and of conventional quantum 1/f noise as an effect which is not based on the collective field state of the particles, but arises from the individual field of each carrier.

The most interesting component of the recombination current is the surface recombination current which plays a major role in the case of infrared detectors with pn junctions. In the case of MIS devices this role is not so important, as our calculation shows. Nevertheless, one should try to reduce both the concentration of recombination centers and the value of the surface potential jump U. This can be accomplished with careful surface treatment, and with a good passivation layer. SiO_2 layers have been successfully used by Radford and Jones in ion-implanted and double - layer epitaxial HgCdTe photodiodes[13].

In general the larger life time of the carriers in MIS devices, compared to junction devices is due to the absence of the damage inflicted by ion - implantation, or by the heavy doping required in double - layer epitaxial photodiodes. The quantum 1/f noise is invesely proportional to this life time. Therefore, MIS devices should have lower 1/f noise. On the other hand, 1/f noise present in the applied gate voltage, in the timing of the readout and the value of the readout potential will be added as a 1/f noise source, if it is present. In the present calculation, however, this noise source has not been included.

Any reduction in the concentration of tunneling centers present in the bandgap will have a positive effect on quantum 1/f noise. As we have seen in Sec. II, p - type devices should yield less tunneling via bandgap centers. The effective mass present in the denominator of the quantum 1/f noise formula in this case should just be the effective mass of the carriers after the tunneling process, i.e., the effective mass of the outgoing carriers emerging from the process we have considered, or the effective mass of the carriers coming in to the process of tunneling toward the centers in the bandgap. Here we have considered the tunneling process as the slower process which actually controls the rate of tunneling via bandgap states. The capture of carriers by the bandgap states is the second part of this compound process and has been considered fast enough, so that it does not limit the rate of the total process. In general, however, both parts of the process have to be considered as a limitation on the rate, and in this case our noise formulae have to be revised through the inclusion of an additional term similar to the recombination noise term.

In the case of very small MIS devices, where only conventional quantum 1/f noise should be present, we may find lower noise in the n - type devices, whose bulk minority carriers are holes with much larger effective masses than the electrons. This may happen in spite of the larger tunneling via bandgap centers located right under the surface of these devices.

Finally, we would like to empahsize that the present study has attempted to explain the basic concepts of quantum 1/f noise and to illustrate their application to MIS infrared detectors. Although we have tried to pursue the calculation all the way to the evaluation of the detectivity, the data which we used in the calculation may not be applicable in the practical case at hand, and may have to be replaced with pertinent data in any concrete case.

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III.6.REFERENCES
(for Sec. III only)

[1] P.H. Handel, "1/f noise, an infrared phenomenon", Phys. Rev., Lett., vol. 36, 1492, (1975).

[2] P.H. Handel, "Quantum approach to 1/f noise", Phys. Rev., vol. A22, p.795, (1980).

[3] P.H. Handel and D. Wolf, "Characteristic functional of quantum 1/f noise", Phys. Rev., vol. A26, 3727, (1982).

[4] G.S. Kousik, C.M. Van Vliet, G. Bosman and P.H. Handel, "Quantum 1/f noise associated with ionized impurities scattering and electron - phonon scattering in cendensed matter", Advances in Physics, vol. 34, 663 - 702, (1985).

[5] A van der Ziel, P.H. Handel, X.L. Wu and J.B. Anderson, "Review of the status of quantum 1/f noise in n^+-p HgCdTe photodetectors and other devices", J. Vac. Sci. Technol., vol. A4, 2205, (1986).

[6] A. Van der Ziel and P.H. Handel, "1/f noise in n^+-p diodes", IEEE Transactions on electron devices, vol. ED - 32, 1802, (1985).

[7] A. Van der Ziel, "Noise in solid state devoces and circuits", J. Wiley & Sons, N.Y. (1986), Ch.11.

[8] X.L. Wu, J.B. Anderson and A. van der Ziel, "Diffusion and recombination 1/f noise in long n^+-p $Hg_{1-x}Cd_xTe$ diodes", IEEE Transactions on electron devices, (1986).

[9] M.A. Kinch, "Metal - insulator - semiconductor infrared detectors", Semiconductors and Semimetals, vol. 18, p. 313 - 378, (1981).

[10] M.A. Kinch and J.D. Beck, "MIS detectors for advanced focal planes", Proc. IRIS Det. Sp. Grp. (Boulder, Co.) (1984).

[11] P.H. Handel, "Any particle represented a coherent state exhibits 1/f noise" in "Noise in physical systems and 1/f noise", edited by M. Savelli, G. Lecoy and J.P. Nougier (North - Holland, Amsterdam, 1983), p. 97.

[12] P.H. Handel, "Coherent states quantum 1/f noise and the quantum 1/f effect" in "Proceedings of the VIIIth international conference on noise in physical systems and 1/f noise" (Elsevier, New York, 1986), p.469

[13] W.A. Radford and C.E. Jones, "1/f noise in ion - implanted and double - layer epitaxial HgCdTe photodiodes", J. Vac. Sci. Technol. A3, p. 183 - 188, (1985).

[14] R.M. Warner, Jr. and B.I. Grung, "Transistors, fundamentals for the integrated circuit engineer", New York, Wiley, (1983).

[15] K.M. Van Vliet, "Noise and admittance of the generation - recombination current involving SRH centers in the space charge region of junction devices", IEEE Trans. Electron Devices, vol. ED - 23, p. 1236, (1976).

[16] Lorteije J.H.J. and Hoppenbrouwers A.M.H., Philips Res. Rep. 26, p. 29 - 39, (1971)

IV. PUBLICATIONS

DURING THE SSP PERIOD 4/15/85-4/14/88

1. A. van der Ziel and P.H. Handel: "Quantum Partition 1/f Noise in Pentodes", Physica 125B, 286-292 (1985).

2. A. van der Ziel, P.H. Handel, X.C. Zhu and K.H. Duh: "A Theory of the Hooge Parameters of Solid State Devices", IEEE Transactions on Electron Devices ED-32, 667-671 (1985).

3. A. van der Ziel and P.H. Handel: "1/f Noise in N -P Diodes", IEEE Transactions on Electron Devices ED-32, 1802-1805 (1985).

4. A. van der Ziel and P.H. Handel: "Quantum 1/f Phenomena in Semiconductor Noise", Physica 129B, 578-579 (1985).

5. P.H. Handel: "Exploration of Fusion Conditions in Radio Frequency Discharge Cavitons", Lasers and Particle Beams 3", 347-349 (1985).

6. A. van der Ziel and P.H. Handel: "Discussion of a Generalized Quantum 1/f Noise Process with Applications", Physica 32B, 367-369 (1985).

7. A. van der Ziel and P.H. Handel: "1/f Noise in p-n Junctions Calculated with Quantum 1/f Theory", Proc. VIII Int. Conference on Noise in Physical Systems and IV Int. Conference on 1/f Noise, Rome, September 1985, North Holland Publishing Co., pp.481-484.

8. P.H. Handel and C.M. Van Vliet: "Quantum, 1/f Noise in Solid State Scattering, Recombination, Trapping and Injection Processes", Ibid, pp. 473-475.

9. P.H. Handel: "Quantum 1/f Noise in Squids", Ibid, pp.489-490.

10. P.H. Handel: "Coherent States Quantum 1/f Noise and the Quantum 1/f Effect", Ibid, pp. 465-468.

11. P.H. Handel: "Gravidynamic Quantum 1/f Noise", Ibid, pp. 477-480.

12. P.H. Handel and A. van der Ziel: "Relativistic Correction of the Hooge Parameter for Umklapp 1/f Noise", Physica 141B, 145-147 (1986).

13. P.H. Handel: "Bolts from the Blue";("Has the Mystery of Atmospheric Electricity Been Solved?"), The Sciences, July/August (1985), p. 43-53.

14. A. van der Ziel, P.H. Handel, X.L. Wu and J.B. Anderson: "Experimental and Theoretical 1/f Noise Study of n^+ -p $Hg_{1-x}Cd_xTe$ Photodetectors", Proc. of the 1985 Workshop on the Physics and Chemistry of Mercury Cadmium Telluride, San Diego, Oct. 8-10, 1985, p. 213-214.

15. G.S. Kousik, J. Gong, C.M. Van Vliet, G. Bosman and P.H. Handel: "Flicker Noise Fluctuations in Alpha Radioactive Decay", Canadian J. of Physics 65, 365-375 (1987).

16. G.S. Kousik, C.M. Van Vliet, G. Bosman and P.H. Handel: "Quantum 1/f Noise Associated with Ionized Impurity Scattering and Electron-phonon Scattering in Condensed Matter", Advances in Physics 34, 663-702 (1986).

17. A. van der Ziel, P.H. Handel, X.L. Wu and J.B. Anderson: "Review of the Status of Quantum 1/f Noise in n^+ -p $Hg_{1-x}Cd_xTe$ Photodetectors and Other Devices", J. Vac. Sci Technol. A4, 2205-2216 (1986).

18. P.H. Handel: "Application of the Quantum Theory of 1/f Noise to MIS Infrared Detector Structures" Unpublished Report.

19. P.H. Handel: "Second-Quantization Formulation of Quantum 1/f Noise", Proc. of the IX International Conference on Noise in Physical Systems, Montreal (Canada), 1987 (Invited paper), C.M. Van Vliet Editor, World Scientific Publ. Co., 687 Hartwell Str., Teaneck, NJ 07666, pp. 365-372

20. P.H. Handel: "Effect of a Finite Mean Free Path on Quantum 1/f Noise", Proc. of the IX International Conference on Noise in Physical Systems, Montreal (Canada), 1987, C.M. Van Vliet Editor, World Scientific Publ. Co., 687 Hartwell Str., Teaneck, NJ 07666, pp. 419-422.

21. P.H. Handel and T. Musha: "Coherent State Piezoelectric Quantum 1/f Noise". Ibid., pp. 413-414.

22. P.H. Handel and Q. Peng: "Quantum 1/f Fluctuations of Alpha Particle Scattering Cross Sections". Ibid., pp. 415-418.

23. P.H. Handel, E. Kelso and M. Belasco: "Theory of Quantum 1/f Noise in n p Junctions and MIS Diodes". Ibid., pp. 423-426.

24. G.S. Kousik, C.M. Van Vliet, G. Bosman, W.H. Ellis, E.E. Carrol and P.H. Handel: "A More Complete Interpretation of Flicker Noise in Alpha Radioactive Decay". Ibid., pp. 121-128.

25. A van der Ziel, C.J. Hsieh, P.H. Handel, C.M. Van Vliet and G. Bosman: "Partition 1/f Noise in Pentodes and its Quantum Interpretation", Physica 145 B pp.195-204 (1987).

26. P.H. Handel: "Answer to Objections against the Quantum 1/f Theory", p.1-39, Submitted to Physical Review.

27. P.H. Handel: "Fundamental Quantum 1/f Fluctuation of Physical Cross Sections and Process Rates", p.1-9, Submitted to Physical Review Letters.

28. P.H. Handel: "Quantum Approach to 1/f Noise II: Fluctuations of Physical Cross Sections", Submitted to Physical Review.

29. P.H. Handel: "Quantum 1/f Effect with a Finite Mean Free Path of the Current Carriers", Submitted to Physical Review.

30. P.H. Handel and T. Musha: "Coherent Quantum 1/f Noise from Electron-Phonon Interactions", Accepted for publication in Z. Physik B.

31. P.H. Handel: "Derivation of Quantum 1/f Fluctuations in Physical Cross Sections", p.1-14, Submitted to Physical Review Letters.

32. P.H. Handel: "Quantum 1/f Cross Section Fluctuations in Condensed Matter Conditions", p.1-6, Submitted to Physical Review Letters.

33. P.H. Handel: "Invalidity of the Kiss-Heszler 'exact proof' and correctness the quantum 1/f noise theory", p.1-7, Accepted for publication in Journal of Physics C: Solid State Physics.

34. Heinrich Hora and P.H. Handel: "New Experiments and Theoretical Development of the Quantum Modulation of Electrons (Schwarz-Hora Effect), Advances in Electronics and Electron Physics 69, 55-113 (1987).

35. P.H. Handel: "Starting Points of the Quantum 1/f Noise Approach", p.1-26, Submitted to Physical Review B.

36. M. Sekine, Y. Okamoto, P.H. Handel, T. Nakamura, Y. Takagi and R. Liang: "High T_c of the Oxide Superconductors", p.1-9, Submitted to Journal of Low Temperature Physics.

37. P.H. Handel: "Characteristic Functionals of Quantum 1/f Noise and Thermal Noise", Proc. 1987 Conf. on Information Theory of the Inst. of Electronics, Information and Communication Engineers of Japan, (IEICE), Osaka, Japan (1987), pp. 125-130.

38. P.H. Handel: "Maser-Caviton Ball Lightning Mechanism", Proc. VIII Int. Conf. on Atmospheric Electricity, Uppsala 1988, accepted for publication.

39. P.H. Handel: "Experimental Evidence on the Polarization Catastrophe Mechanism of Cloud Electrification", Proc. VIII Int. Conf. on Atmospheric Electricity, Uppsala 1988, accepted for publication.

40. P.H. Handel: "Infrared Divergences, Radiative Corrections and Bremsstrahlung in the Presence of a Thermal Equilibrium Radiation Background", Phys. Rev. (1988) accepted for publication

Note: Papers with no page and volume numbers listed are submitted for publication, and are still in the reviewing process or in process of publication, but not yet published.

Papers # 5, 13, 38 and 39 are not connected to SSP matters, but were included for completeness.